Tidal Channels of Skagit Bay: Three-Dimensional Hydrodynamics and Morphodynamic Evolution

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LONG-TERM GOALS

To measure and model the dynamics of currents, waves, and sediment transport over tidal flats, with particular emphasis on interactions between water flows and bathymetry. To improve insight and predictive capabilities through model-data comparisons.

OBJECTIVES

1. To measure water flows and bathymetric evolution within and around the tidal channels of Skagit Bay.
2. To explain and model observed flow patterns.
3. To explain the observed interactions between hydrodynamics and bathymetric evolution.

APPROACH

During FY2011, we worked to analyze data collected during field experiments in FY2008-2009, to develop and test models, and to publish our results in peer-reviewed journals. During the field experiments we deployed arrays of instruments, especially Acoustic Doppler Current Profilers (ADCPs), to resolve in detail the vertical and horizontal variations in flows within and near tidal channels. Multi-month deployments of fixed instruments measured the persistent flows responsible for bathymetric evolution (Figure 1). Repeated GPS surveys measured bathymetric evolution (Figure 2). Water properties and currents were found to vary across sharp boundaries just tens of meters thick (Figure 3) and tens of centimeters deep. To resolve these observed spatial gradients, brief intensive deployments of mobile current meters, CTDs, and GPS drifters provided unique high-resolution flow measurements (Figure 4). Data were posted on the web for use by other researchers in the tidal flats DRI.

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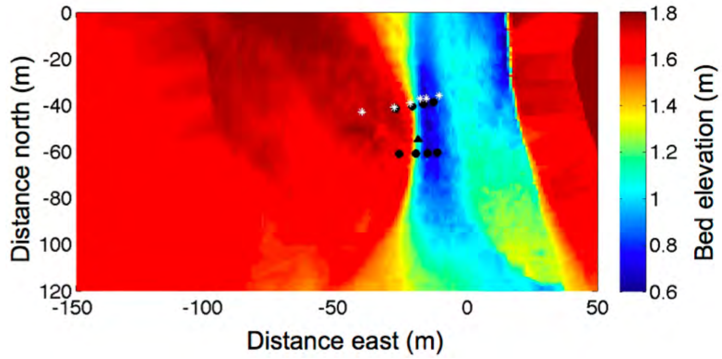

Figure One: Locations of fixed instruments during May (white stars) and June–August (ADCPs black circles, vertically-spaced CTDs black triangle). Color scale indicates bed elevation, with periodically-flooded tidal flats marked by red area, and permanently-flowing tidal channel marked by blue-green. [During May, six instruments were deployed in a single 40-m-long transect extending from tidal flats and across the curved western edge of a 40-m-wide, 1.2-m deep tidal channel which runs north-south. During June-August, two 4-instrument, 20-m-long transects crossed the channel-edge. These two transects were displaced by 20m in the along-channel direction.]

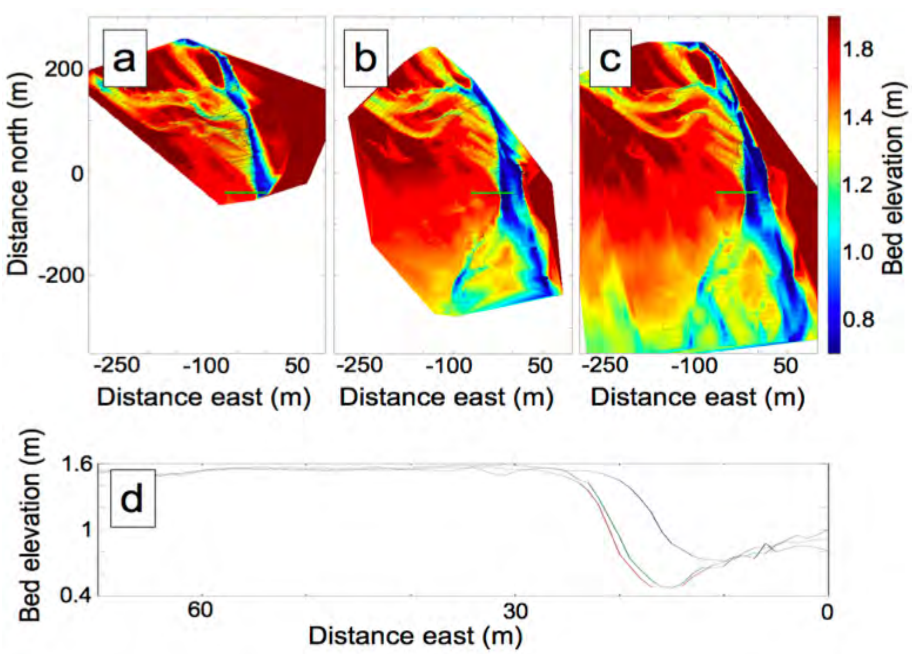

Figure 2: Bathymetric surveys for May (a) June (b) and July (c) 2009 (further surveys from Sept 2008, late July 2009, and August 2009 not shown). Cross-sections through surveyed channel edge bathymetry (d) for May (blue) June (green) and July (red) (location of cross-sections is indicated in (a)–(c) by green line). [Repeated bathymetric surveys in a 300 m by 500 m region show a tidal channel surrounded by unmoving tidal flats. Cross-sections show that the channel edge moved about 10 m between May and June.]

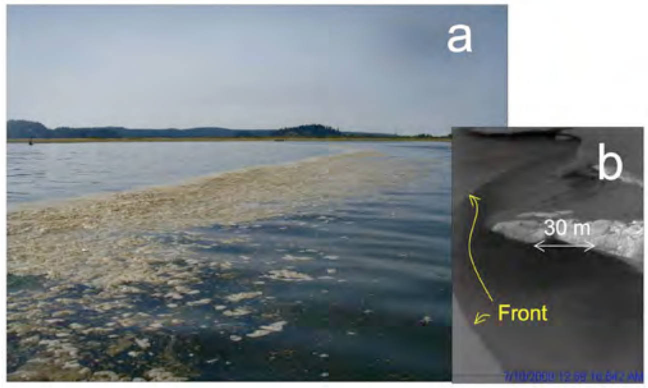

Figure 3: Visual (left) and infrared (right) images of channel-edge surface fronts (IR image provided by Thompson and Chickadel).
[Fronts on the ocean surface are clearly marked by a streak of foam (visual image) and a sharp brightness contrast (IR image, marking a jump in surface temperature).]

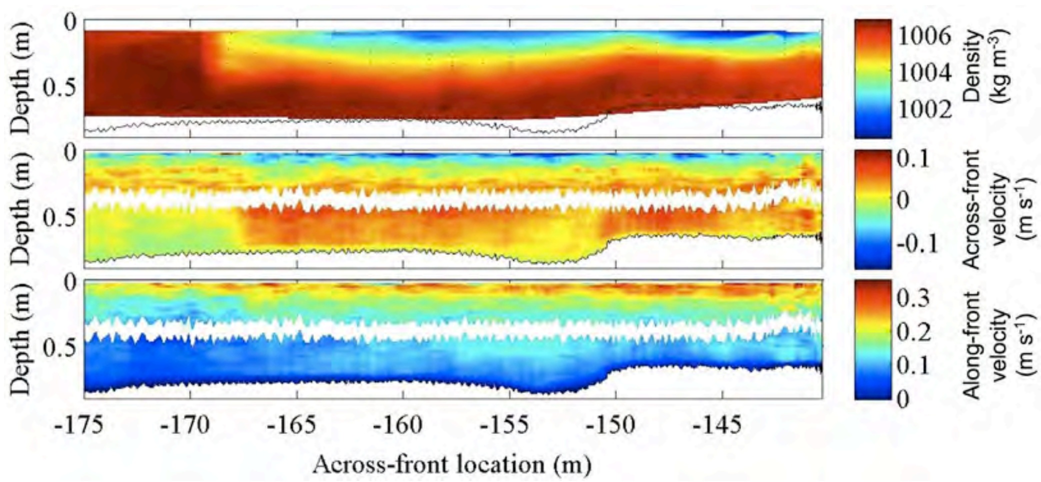

Figure 4: Transects of density and velocity across the edge of a fresh surface plume.
[Density, velocity, and depth are plotted as functions of depth and distance. Fresh plume visible as low-density layer less than 0.5 m thick. Top of fresh layer is moving towards plume, underlying layer is moving away. Both along- and across-front velocities are strongly sheared at the base of the plume.]

To simulate the density-driven flows observed near the channel-edge, we have used analytic and numerical models that have been widely applied in deeper water. To simulate the dissipation of waves within a saltmarsh neighboring the channel, we have derived and tested novel analytic and numerical models. To understand the propagation of thin surface layers of freshwater across the flooded tidal flats, we have combined flow measurements with equations for conservation of mass, momentum, and energy. Ongoing work aims to examine interactions between hydrodynamics and bathymetric

evolution, by substituting flow measurements into simple sediment transport formulas, and compare predictions with observed morphological evolution.

Key individuals include Stephen Henderson (PI), Julia Mullarney (a Postdoctoral Researcher helping to coordinate fieldwork and undertake analysis), and graduate students Kassondera Riffe and Alyson Day (contributing to fieldwork and analysis).

WORK COMPLETED

Work in FY11 has built on the field observations collected in previous years.

During FY-11, our group has published three papers on our ONR-funded tidal flats research in leading peer-reviewed journals. A fourth paper has been submitted to a Tidal Flats special issue of the peer-reviewed journal "Continental Shelf Research". A fifth paper is in an advanced stage of preparation, and an additional abstract has been submitted to the publication "Proceedings of the International Conference on Coastal Engineering".

Masters student Alyson Day has completed most coursework and has collated data on the channel-edge flows responsible for measured channel migration. Masters student Kassondera Riffe successfully defended her thesis, graduated, and published her work in a leading peer-reviewed journal.

RESULTS

We have found that hydraulic control theory explains the formation of intense baroclinic fronts along the edges of tidal channels during the early stages of flood tide (figure 3). We showed that this mechanism may be widespread in shallow tidal-flats flows, because even weak (10m/s) flows are often supercritical during the early stages of flood tide. Mixing at these fronts was of intermediate intensity (Hogg *et al*. 2001). The strongest near-bed across-channel flows we observed were generated by these fronts, a fact potentially significant to channel bathymetric evolution.

We found that thin (sometimes only 0.3-m-thick) surface plumes of relatively fresh water can persist for hours, carrying river water kilometers across the tidal flats (figure 4). We quantified energy balances and mixing rates along the fronts bounding these plumes. One interesting result is that strong shear of the along-front velocity contributes significantly to mixing (such along-front shear is absent in laboratory and theoretical models for gravity current propagation). One front propagated for 1.5 hours over the tidal flats before encountering a strongly-sheared opposing barotropic current an suddenly dissipating. We are working to test models against these observations, with the aim of improving predictions of freshwater spreading and mixing across tidal flats.

Even under the weak winds that prevailed during our 2009 experiment, winds were responsible for a substantial proportion of the vertical variability of observed currents. We found intriguing patterns in this vertical variability: midway between the bed and the surface, shear simply increased with increasing windspeed. This behavior was explained by a simple eddy viscosity model that neglected effects of wave-generated mixing. In contrast, near-surface shear was oriented in the wind direction, but did not increase in strength with increasing windspeed. We developed a simplified model (based on more complex previous models for mixing by breaking waves) to show that wave-generated mixing prevented the development of strong shear under strong winds.

We measured wave dissipation in a saltmarsh adjacent to the tidal flats, and found that most wave energy was dissipated within 10m of the marsh edge, providing still water ideal for deposition of fine sediments. We adapted the Euler-Bernuolli equations for beam bending, widely used by structural engineers, to simulate wave dissipation by flexible saltmarsh vegetation. Analytic and numerical solutions were derived, and were found to agree with vegetation motion observed using synchronized current meters and video (Figure 5). These results show that vegetation motion can cause substantial reductions in wave dissipation, and that this effect can be predicted by a simple analytic model.

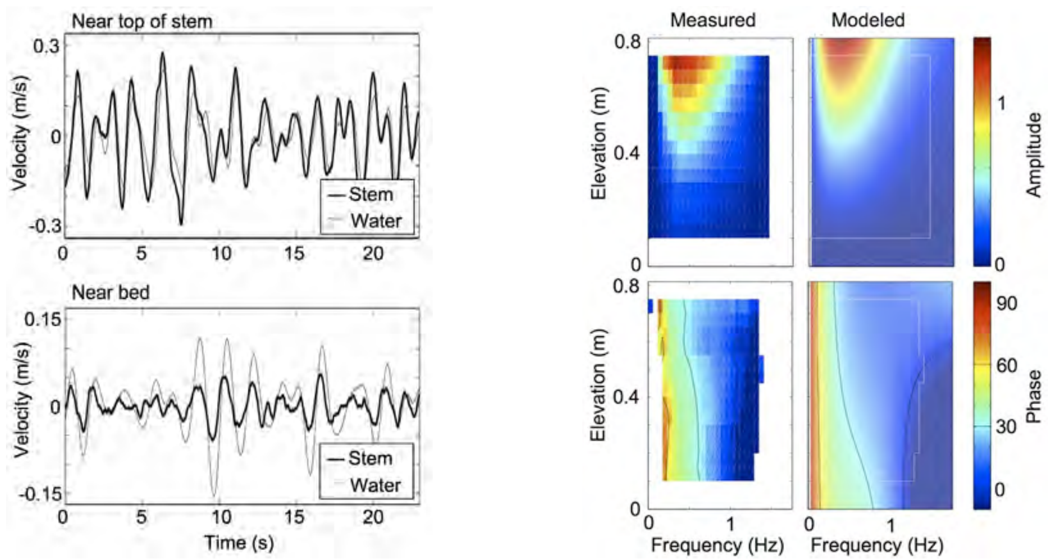

Figure 5: Left: Observed motion of water and flexible stem in saltmarsh at two elevations above the bed. Right: Measured and predicted transfer function between water and stem motion (stem free end at 0.8 m).
[Observations near the top of a stem show stem and water move back and forth together under waves. Observations near stem base show stem motion smaller than wave motion, and leading wave motion by ¼ of a cycle. Theoretical and observed transfer function amplitudes show that stem motions are largest relative to water motions near stem free end, and at frequencies about 0.5 Hz. Theoretical and observed transfer function phases show that stem motions lead water motions by ¼ of a cycle at frequencies below about 0.1 Hz, but smoothly transition to being in phase at frequencies above about 0.8 Hz. Model-data agreement is good.]

IMPACT/APPLICATIONS

The fronts we measured are clear to remote sensors. Hydraulic control processes, which closely link frontal dynamics with bathymetry, could prove useful in the development of bathymetric inversion algorithms.

Buoyant plumes distribute river water and fine sediments. Observations of plume propagation and mixing provide an opportunity to improve understanding of mechanisms for transport of salt, heat, and

fine sediment across tidal flats. Improved understanding of wind-generated currents may also improve understanding and prediction of such transport.

Both fresh plumes and winds caused substantial (up to 0.3 m/s) variations in velocity within 0.4 m of the water surface. Such near-surface velocity variations might be important in interpreting remotely-sensed surface velocities, and in comparing remotely-sensed velocities with in-situ measurements, which are often made more than 0.4~m from the surface.

The surface velocities and shears we observed and simulated are likely important to the spreading of buoyant pollutants.

Understanding of wave dissipation by vegetation may improve understanding of fine sediment deposition, since many environments of rapid deposition include substantial saltmarshes.

A long-term goal is the development of accurate models for sediment transport across tidal flats. Testing the ability of sediment transport models to predict bathymetric evolution observed on tidal flats may contribute towards this goal.

RELATED PROJECTS

Our project is a component in a wider Tidal Flats DRI. Our fixed data is available to other Tidal Flats researchers on the web. We have passed our ADCP data to Arete Associates, to help them test their remote estimates of surface velocity.

In support of Tidal Flats researchers Tim Milligan, Paul Hill, and Brent Law, we have also measured currents in Willapa Bay. We worked with these researchers to compare turbulent dissipation rates estimated using our current meters with sediment flocculation estimated using their co-located instruments.

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